OPERATION OF THE C-BAND 50 MW KLYSTRON WITH SMART MODULATOR

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Abstract

An original C-band (5712-MHz) 50-MW klystron (TOSHIBA-E3746) was successfully developed and operated producing 50 MW of peak output power, a 2.5 μsec pulse width and 50 pps repetition rate.

Over a wide range of operating conditions, agreement within a few percent was found between values calculated (by FCI code) and experimentally measured results for the rf output power, gain and conversion efficiency (43%).

A new inverter type DC high voltage power supply successfully drove the 50 MW class klystron at a PFN voltage of 48 kV, with a pulse width of 5.2 μsec (FWHM) at the klystron beam voltages, and pulse repetition rates up to 50 pps. Voltage variations and flatness of the flattop of the klystron beam voltage obtained were less than ±0.17% (at 3σ) and ±0.5% at 350 kV, respectively.

A low inductance current return circuit between the PFN and klystron body was essential to reduce electromagnetic noise radiation during thyratron turn on.

It was confirmed that the required C-band frequency components are manufacturable with current technology available industrially.

1 INTRODUCTION

The aim of the first phase of the Linear Collider project (LC-I) in Japan is to build a new high energy electron-positron linear collider for the 300-500 GeV C.M. energy region. For the LC-I, the klystrons will be of the 50-100 MW class, and the accelerator will have to accommodate more than 4000 of them [1]. In such a large-scale machine, the total component count is extremely large and no laboratory yet has any experience in operating, or in fabricating, so many accelerator devices. Thus, reliability, availability and maintainability are important considerations.

We chose the C-band frequency, because the needed technologies should be available from industrial sources with realistic margins and tolerances.

Hardware R&D on the C-band (5712 MHz) rf-system started in 1996 at KEK. In September 1997, we developed the first 50 MW klystron (see figure 1), its modulator power supply (Smart Modulator), and all the high power wave-guide components. A smart modulator was first proposed for rf systems by Drs. M.H. Cho (PAL, Pohang Accelerator Laboratory) and H. Matsumoto (KEK) in 1993. The motivation was to satisfy the needs of various applications not only for the linear colliders, but also for the scientific and the industrial applications.

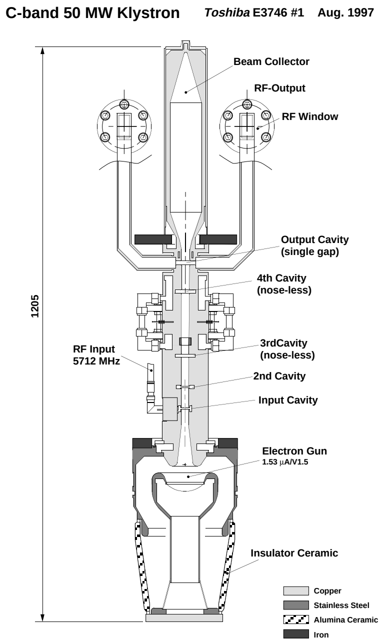

Figure 1: A cross-sectional view of the first C-band 50 MW klystron (TOSHIBA-E3746).

Drs. P. Pearce (CERN-PS) and J.S. Oh (PAL-LINAC) supported us in the R&D work. Presently, the klystron and the smart modulator are available on a commercial basis from TOSHIBA Co., and NIHON KOSHUHA Co., Ltd., respectively.

Currently, the klystron and the smart modulator are running at KEK almost continuously at close to their maximum specifications. We have obtained excellent results, proving possibilities for a wide range of applications in scientific and industrial fields.

In this paper we report on the high power operational status of the first C-band 50 MW klystron and the new concept for the smart modulator.

2 C-BAND 50 MW KLYSTRON

2.1 Design concept

In order to ensure high reliability of the C-band klystron, we decided on a ceiling value of 300-400 Joule/pulse for the beam power in the klystron [2]. This limit comes from safety considerations for beam-power density in drift-tubes.

To guarantee long lifetime, we decided to keep the maximum cathode emission loading less than 10 A/cm^2; and the maximum surface electric field gradient of the electrodes was designed to be 22.1 kV/mm, which is same level as in S-band klystrons such as the SLAC-5045 (350 kV, 50 MW) or TOSHIBA-E3712 (370 kV, 80 MW). As a result, the gun voltage and the required beam current are 350 kV and 320 A, assuming a conversion efficiency of 45%.

2.2 Design parameters

FCI code (Field Charge Interaction code) was used to design the parameters and to simulated the target performance as listed in Table 1 [3].

Table 1: Main parameters of the klystron.

Parameters		Unit
Frequency	5712	MHz
Output rf power	50	MW
RF pulse width (max.)	3.0	μsec
Beam voltage	350	kV
Beam current	317	A
Power efficiency	45	%
Gain	>50	dB
Repetition rate	50	pps
Perveance (10^{-6})	1.53	$A/V^{1.5}$
Cathode loading	6.3	A/cm^2
Type of cathode	Dispenser scandate	
Cathode electrode martial	Stainless-steel*	

* "Clean-Z": product by NKK Co., Ltd., Japan

The klystron has five cavities and two output waveguide circuit arms, connected to a nose-less single gap output cavity to maintain the field symmetry. The gun has cathode 74.5 mm in diameter, which corresponds to an average cathode beam loading of 6.3 A/cm^2. The cathode electrode material was carefully chosen to be very high quality stainless steel (SUS316L, "Clean-Z") to avoid discharge breakdown due to contaminated near the electrode surface [4].

Further, we introduce a spring contract at the electron gun housing to improve the current flow from the klystron body back to the PFN return circuit shown in figure 2. This is very effective in reducing electromagnetic noise.

Two rf windows, which propagates the traveling-wave field were used to provide enough margin in power transfer. A simple long pillbox shaped rf window was designed to reduce the electric field in the ceramic disk as well as increase the mass predictability [5]. The frequency bandwidth where the reflection coefficient (S_{11}) is 0.1 or less is 500 MHz.

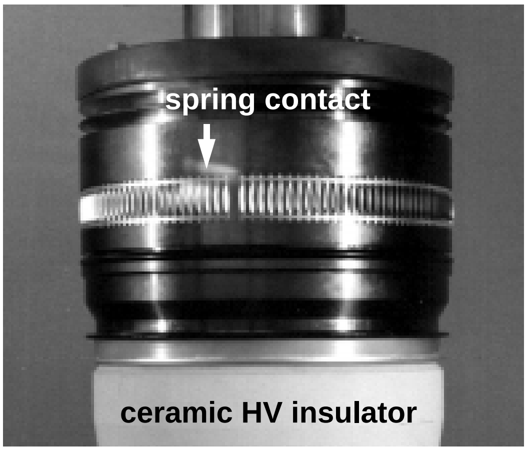

Figure 2: Metal spring contact for return current from the klystron body.

2.3 High power operation

After 140 hours of conditioning, the first klystron achieved 50 MW peak output rf power, 1.0 μsec pulse width and 50 pps repetition rate.

Figures 3 and 4 show the measured characteristics of the klystron (TOSHIBA-E3746), showing the efficiency, rf output power and power transfer curves. Over the operating range, agreement was found within 2% between simulation (FCI code) and experimental results. A very good rf power flattop can be seen in figure 5. No

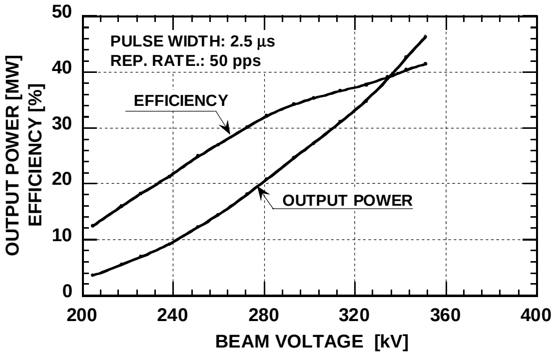

Figure 3: Typical efficiency and rf output power characteristics at saturation as a function of beam voltage.

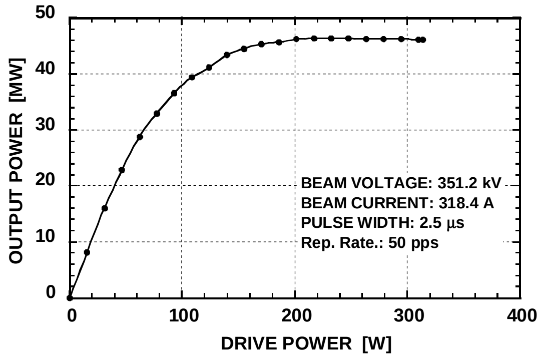

Figure 4: Typical transfer characteristic as a function of rf drive power.

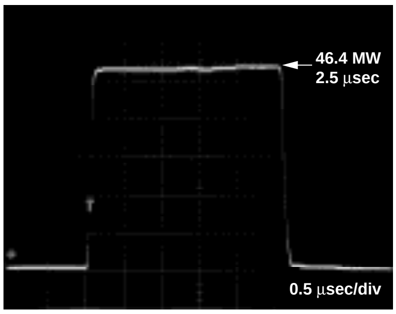

Figure 5: Output rf power at a beam voltage of 351 kV and repetition rate of 50 pps.

oscillation was observed in the waveform.

3 SMART MODULATOR

3.1 Design concept

In general, klystron modulators suffer from many diverse troublesome problems, such as unreliability, large electromagnetic noise emissions, and bulky sizes as well as being an expensive part of the accelerator system. The reasons being that they typically use so many high voltage and high power components, such as the thyratron and capacitors etc.; and after all it must generate pulsed high voltage at high current. Thus, in spite of the need for improvement, modulator power supplies have not changed in many years in Japan.

To reduce the modulator size and remove the de-Qing circuit from the PFN, we began by introducing an inverter-type DC-HV power supply instead of the conventional rectifier type supply. We tried the EMI-303 (Electric Measurement Inc., USA) inverter type DC-HV power supply, whose size is only 48 cm wide, 31 cm high and 56 cm deep. It generates a maximum output voltage of 50 kV and an average power of 30 kW (or 37.5 kJ/sec); this can drive the 50 MW klystron up to 50 pps repetition rate at 350 kV beam voltage given a 1:15 step-up transformer. The voltage regulation of the EMI-303 is tighter than ±0.5% at a 200 pps charging cycle so that there is no longer any necessity of having a de-Qing system in the PFN circuit [6].

To reduce the electromagnetic noise radiation, we created a low inductance (or impedance) path for the return current from klystron body to PFN return circuit, based on the general theory of pulse circuits. We used a simple wide thin copper plate, 30 cm wide and 0.1 mm sthick [7].

3.2 High power operation

The first smart modulator tested at KEK demonstrated a PFN voltage of 48 kV, pulse width (FWHM) of 5.2 μsec at the klystron and 50 pps.

Figure 6-a shows the typical charging and discharging PFN voltage waveform at a 50 pps repetition rate. The EMI-303 inverter power supply takes 13.6 ms at its maximum charging speed to get to a PFN voltage of 47.5 kV. The calculated single bucket voltage and the stored energy of the inverter power supply is 62 V and 0.7 Joule/bucket with the 56 kHz switching cycle as shown in figure 6-b. The single bucket energy is only 0.16% of the peak PFN stored energy (438 Joule). This will help extend the thyratron lifetime as compared with the usual operation. The voltage variation of the EMI-303 is ±0.13% at an output voltage of 47.5 kV as calculated from the measured data shown in figure 6-b.

The typical waveforms of beam voltage at 350 kV are shown in figure 7-a. The flattop of the beam voltage was found to be within the ±0.5% over the 2.5 μsec width (see figure 7-b). This is good enough for the C-band rf system [8]. The measured klystron beam voltage variation was found to be within ±0.17%, which is close to the voltage regulation of the EMI-303 power supply.

4 CONCLUSIONS

The first C-band klystron and inverter type DC-HV power supply confirmed their reliabilities for actual accelerator application. The required technologies for the C-band components are available from industry with good enough manufacturability margins.

5 REFERENCES

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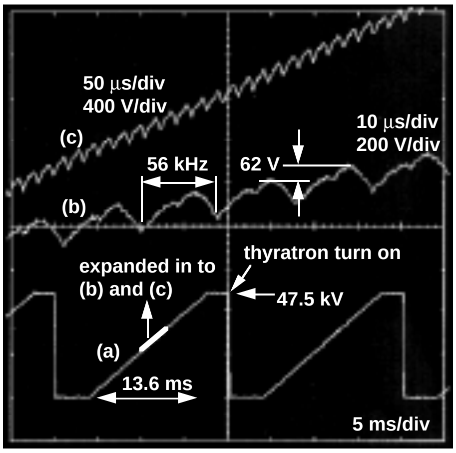

Figure 6: (a): PFN charging voltage waveform at 50 pps. (b) and (c): expanded view of the PFN charging voltage. Measured voltage variations is 0.13% at a PFN charging voltage of 47 kV.

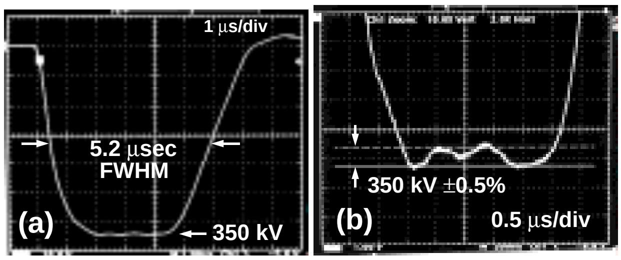

Figure 7: (a): klystron beam voltage waveform at 350 kV and 5.2 μsec. (b): expanded beam voltage of the flattop.